Eur. Phys. J. C (2011) 71:1692
DOI 10.1140/epjc/s10052-011-1692-4

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Fluctuations and asymmetric jet events in PbPb collisions at the LHC

Matteo Cacciari[1,2,a], **Gavin P. Salam**[1,3,4], **Gregory Soyez**[5]

[1]LPTHE, UPMC Univ. Paris 6 and CNRS UMR 7589, Paris, France
[2]Université Paris Diderot, Paris, France
[3]Department of Physics, Theory Unit, CERN, 1211 Geneva 23, Switzerland
[4]Department of Physics, Princeton University, Princeton, NJ 08544, USA
[5]Institut de Physique Théorique, CEA Saclay, CNRS URA 2306, 91191 Gif-sur-Yvette, France

Received: 14 February 2011 / Revised: 2 June 2011 / Published online: 29 June 2011

Abstract Recent LHC results concerning full jet-quenching in Pb Pb collisions have been presented in terms of a jet asymmetry parameter, measuring the imbalance between the transverse momenta of leading and subleading jets. We examine the potential sensitivity of this distribution to fluctuations from the heavy-ion background. Our results suggest that a detailed estimate of the true fluctuations would be of benefit in extracting quantitative information about jet quenching. We also find that the apparent impact of fluctuations on the jet asymmetry distribution can depend significantly on the choice of low-p_t threshold used for the simulation of the hard pp events.

In the quest to understand the properties of the medium generated in high-energy heavy-ion collisions, the past decade has seen extensive study of medium-induced modifications to the production of high transverse momentum objects [1–6]. It has been conclusively established at RHIC that the spectra of high-momentum hadrons are significantly suppressed, by a factor of $R_{AA} \simeq 0.2$ relative to the appropriate rescaling of the pp spectra. This effect is generally attributed to their (or their originating parton's) interaction with the medium.

Recently, significant attention has been directed to jets. Compared to hadrons, jets are interesting because, at least in pp collisions, there is a closer, and perturbatively quantifiable, connection between a jet's momentum and that of its originating parton. STAR [7–10] and PHENIX [11] have presented first (preliminary) measurements of full jets produced in AuAu collisions with transverse momenta in the 20–40 GeV range and found that jet spectra are also suppressed, though by a potentially more modest factor than for hadrons. Recently, ATLAS [12] has published studies of the *correlations* between the momenta of the two leading jets, with the striking observation that a significant fraction of events show a strong imbalance between the p_t's of the leading jet and the first subleading jet on the opposite side of the event. CMS has shown similar preliminary results in Ref. [13][1] and first phenomenological interpretations have been given in Ref. [15].

Dijet imbalances can occur also in normal pp events, due to emission of multiple gluons (cf. the simulated Pythia event shown in Fig. 1), but they are quite rare. To quantify how much more often they arise in Pb Pb collisions, ATLAS and CMS have shown distributions of the jet asymmetry A_J

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \tag{1}$$

expressed in terms of the transverse energies of the leading and subleading jets, respectively E_{T1} and E_{T2}. The main quantitative evidence for jet quenching comes in the form of a significant enhancement of the asymmetry in the region around $A_J \simeq 0.4$ (Fig. 3 of [12] and p. 26 of [13]).

In extracting the distribution of A_J, the experiments must contend with the fact that each jet may be contaminated with $\mathcal{O}$ (100–150 GeV) of transverse momentum from the medium particles, usually referred to as the background.[2] To calculate the A_J for a given dijet event, each jet's momentum is corrected for the expected level of background activity in the jet, usually estimated from the activity elsewhere in the event, preferably at similar rapidities (see e.g.

[a] e-mail: cacciari@lpthe.jussieu.fr

[1]Subsequently published in [14].

[2]The distinction between medium particles and jet particles is not necessarily very legitimate physically, however it may still make sense to think of an expected level of background transverse momentum.

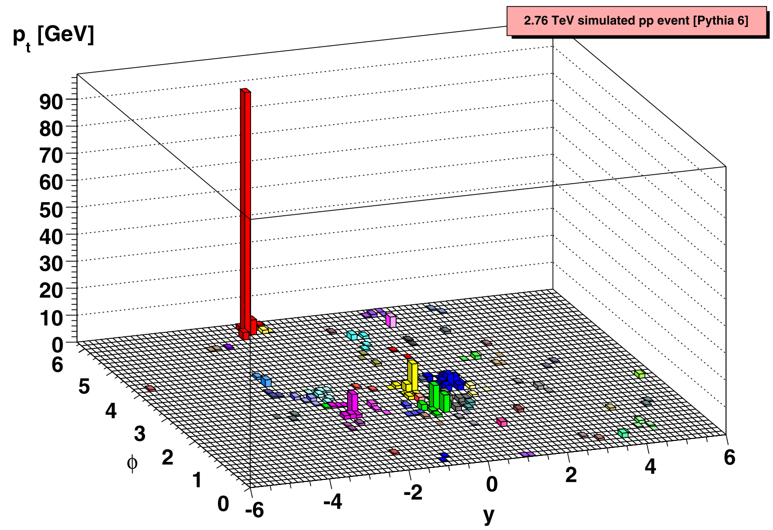

Fig. 1 A simulated pp event from Pythia 6.423 (centre-of-mass energy $\sqrt{s} = 2.76$ TeV; the missing transverse energy was zero). We find that for 1 in every 300 events with a jet with $p_{t1} > 100$ GeV, the second hardest jet has $p_{t2} < p_{t1}/3$. A more accurate estimation of this number would benefit from the combination of 2-jet, 3-jet, 4-jet, ... samples, using for example one of the multijet matching methods reviewed in [16]

[12, 17, 18]). Such a correction cannot, however, account for the fact that the background fluctuates from point to point within the event (even at the same rapidity), so that the momentum subtracted from the jet will inevitably differ from the background actually present in the jet; nor does it account for fluctuations in the detector's response to the background and jet particles.

Fluctuations are of course a common issue for jet measurements even in pp collisions, notably due to randomness in the response of calorimeters. However two novelties may be relevant concerning fluctuations for heavy-ion collisions. Firstly the LHC heavy-ion medium has only just been produced and it is probably fair to assume that its fluctuations[3] are less well understood than those of the detectors, which have been the object of study for many years. Secondly, the absolute size (i.e. in GeV) of detector fluctuations scales roughly as the square-root of the jet energy, meaning that they are less important for low-p_t jets than for high-p_t jets, whereas background fluctuations are probably largely independent of the jet's p_t.

This last point is relevant because of the way in which fluctuations can affect the A_J distribution. The experimental analyses of the A_J distribution select events in which the leading jet passes some high-p_t cut, say $p_t > 100$ GeV. Events with a genuine high-p_t jet are rare. There are many more low-p_t dijet events and in some small fraction of cases the background under one of the jets may fluctuate upwards causing the jet to pass the high-p_t cut. Such events will naturally have a large jet asymmetry, since there is no reason for the balancing jet to also have a positive background fluctuation. The relative contributions of different classes of events depends on the interplay between the rareness of large background fluctuations and the rareness of high-p_t jet production as compared to low-p_t jet production. While one can in principle estimate the potential severity of this problem from Monte Carlo simulations, it is debatable whether reliable enough descriptions of the PbPb medium produced at high energy exist. Guidance from experimental measurements is therefore paramount.

One parameter that is indicative of the size of the fluctuations in the reconstructed jet p_t is their standard deviation, which we call σ_{jet}. ATLAS [19] has presented preliminary results for the fluctuations from one calorimeter tower to the next. If scaled up by the square-root of the number of towers in a jet (about 50 for an $R = 0.4$ jet with towers of size 0.1×0.1 in rapidity and azimuth), it would suggest a value $\sigma_{\text{jet}} \simeq 8.5$ GeV for the most central set of events. On the other hand, the scaling of the tower fluctuations by the square-root of the number of towers may not be a safe way of extrapolating tower fluctuations to σ_{jet}, insofar as the background could well have local correlations (there is no clear reason for the correlation length of such fluctuations to necessarily be smaller than the calorimeter tower size). Furthermore there can be other factors that contribute to a degradation of resolution, such as back reaction [20] and fluctuations in the event-by-event (or calorimeter-strip) estimation of the background level (as discussed in Sects. 3.5 and A.1 of [18]).

Another way in which one may attempt to deduce the level of the fluctuations is from a preliminary inclusive jet spectrum for 0–100% centrality (p. 41 of [19]), which displays a region of near Gaussian p_t-dependence for $p_t \lesssim 50$ that is strongly suggestive of an origin due to fluctuations, and compatible with $\sigma_{\text{jet}} \simeq 14$ GeV. One would then expect the corresponding σ_{jet} for 0–10% central events to be somewhat larger.

Neither of the above estimates, made in the original version of this article, is ideal. One criticism that has been made

[3] Including their standard deviation, correlations from point to point within the event, non-Gaussianities, etc.

is that the tower fluctuations do not include full calibration. As for the inclusive jet spectrum, it mixes a genuine jet spectrum in with the fluctuations. However, subsequently, support for $\sigma_{\rm jet}$ values $\gtrsim$15 GeV has appeared in the form of a preliminary measurement of the background fluctuations for charged-track jets from ALICE [21]. It is discussed in detail in Appendix A.2.

To provide simple insight into the impact on the dijet asymmetry from various values of $\sigma_{\rm jet}$, we have carried out the following "toy" analysis. We generate jet events with Pythia [22] (version 6.423, DW underlying-event tune [23]). To mimic the effect of residual fluctuations following background subtraction, we then add to the p_t of each jet a random fluctuation, generated according to a Gaussian distribution with mean 0 and standard deviation $\sigma_{\rm jet}$, independently of the jet p_t (details are given in Appendix A.1). These choices correspond to a perfect estimate of the average background that needs subtracting in each event, with $\sigma_{\rm jet}$ encoding the combination of all sources of fluctuations, whether intrinsic fluctuations of the background, or fluctuations in the detector's response to it. We select events in which the leading jet has $p_t > 100$ GeV, the subleading jet has $p_t > 25$ GeV, both have rapidities $|y| < 2.8$ and are separated in azimuth by $|\Delta\phi| > \pi/2$ and for these events plot the corresponding distribution of A_J, similarly to the ATLAS analysis [12].

The filled black points in Fig. 2 show our results for four different values of $\sigma_{\rm jet}$. One sees a clear distortion of the A_J distribution as $\sigma_{\rm jet}$ is increased, reminiscent of the pattern seen by ATLAS and CMS with increasing centrality. One key element of our simulation is that in generating the filled black points we chose a fairly low minimum p_t cut, $p_t^{\rm min} = 30$ GeV, for the underlying Pythia $2 \to 2$ scattering, and also verified that further lowering this cut made no difference for our values of $\sigma_{\rm jet}$. With a larger choice, $p_t^{\rm min} = 70$ GeV (shaded region),[4] which would be perfectly adequate for low $\sigma_{\rm jet}$, one notices that a significant part of the effect of the background fluctuations can be missed for larger $\sigma_{\rm jet}$. This leads to the obvious implication that the choice of $p_t^{\rm min}$ can play an important role, especially if $\sigma_{\rm jet}$ happens to be large (or, as we have also found, if there are significant non-Gaussianities in the fluctuations[5]).

A complementary investigation into the impact of fluctuations can be obtained by embedding Pythia events into a simulated PbPb background. A similar investigation was carried out by ATLAS, embedding events into PbPb events as simulated by an ATLAS-specific version of HIJING [28]. Our analysis will differ in that we study HYDJET [29, 30] rather than HIJING and use also a lower p_t cutoff for the Pythia events. The tune we use for HYDJET[6] gives an average background level of 210 GeV per unit area for 0–10% centrality and $|\eta| < 2.8$, compatible with the average jet contamination found by ATLAS, and an average charged-particle multiplicity for 0–10% centrality of 1400 for $|\eta| < 0.5$, which is reasonably consistent with that measured by ALICE [31, 32] (further comparisons are discussed in Appendix A.2). HYDJET's simulation of quenching has been turned off, to avoid the potential confusion that might arise from the quenching of hard jets associated with the PbPb simulation rather than with the embedded Pythia event (quenching has only a modest 5–10% effect on the HYDJET fluctuations). Since detectors can have an impact on fluctuations, we have also processed the events through a simplified calorimeter simulation.[7] To subtract the background from jets we have taken the area/median method of [20, 33], using, for the estimation of the background density, a (rapidity) StripRange of half-width 0.8 centred on the jet to be subtracted, as described in more detail in [18]. This method should perform similarly to the ATLAS method of background subtraction. With this setup, for collisions in the 0–10% centrality range, we find fluctuations per unit area of about 23 GeV corresponding, for anti-k_t jets of radius $R = 0.4$, to an expected $\sigma_{\rm jet}$ of 16 GeV and a measured $\sigma_{\rm jet}$ of 17 GeV.

The results we obtain from the HYDJET+Pythia simulations are presented in Fig. 3 for four centrality ranges. The empty circles labelled *"pp" reference* correspond to plain Pythia results as for Fig. 2. The filled black points and shaded histogram correspond to our embedding in HYDJET events and differ only by the $p_t^{\rm min}$ of the underlying Pythia $2 \to 2$ scattering: 10 GeV has been used for the former and 70 GeV for the latter.[8]

The evolution of the A_J distribution with increasing centrality in HYDJET displays a pattern similar to that observed

[4] We understand that this was the value used in Refs. [12, 19].

[5] Significant non-Gaussianities have been observed in [24].

[6] The tuning parameters used to simulate LHC events at $\sqrt{s} = 2.76$ TeV with HYDJET v1.6 have been extrapolated between the 200 GeV (RHIC) and 5.5 TeV (LHC at designed energy) values used in [18] (footnote 7), namely `nh` = 25600, `ylfl` = 3.9, `ytfl` = 1.46 and `ptmin` = 7.54 GeV. Quenching effects have been switched off by setting `nhsel` = 1. The embedded events come from Pythia version 6.423, tune DW, run at $\sqrt{s} = 2.76$ TeV.

[7] Charged particles with $p_t < 0.5$ GeV are first removed, and the remaining particles are put on a calorimeter of size 0.1×0.1 extending up to $|\eta| = 5$ with uncorrelated Gaussian fluctuations of standard-deviation $0.8/\sqrt{E}$ in each tower and a 0 GeV tower threshold. This simple procedure gives a resolution that is 5–10% better than the true ATLAS calorimeter resolution; the comparison and other relevant points are discussed in Appendix A.3. The number quoted above for the average energy flow and fluctuations are those obtained at calorimeter level.

[8] HYDJET itself generates many additional pp $2 \to 2$ scatterings for each heavy-ion collision, each with `ptmin` = 7.54 GeV. When embedding a jet event with a 10 GeV cutoff, in most cases the two hardest jets actually originate from these additional HYDJET pp scatterings.

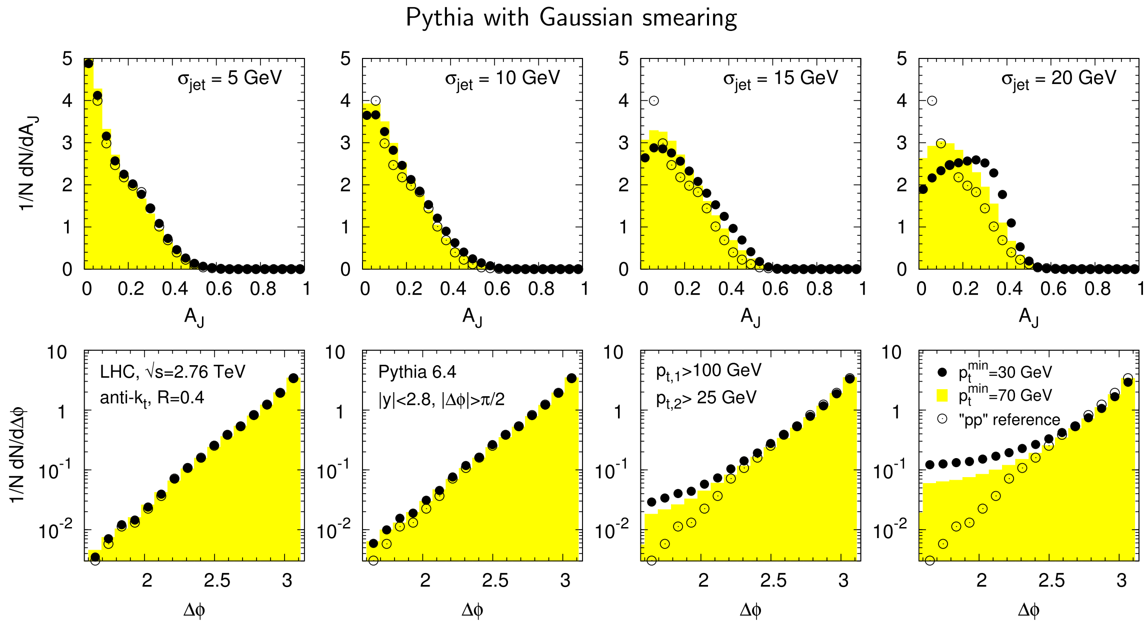

Fig. 2 Simulated distribution of A_J and $\Delta\phi$, as obtained when smearing the p_t of jets from Pythia 6.4 (DW tune [23]) by an amount σ_{jet}. None of the results in this figure involved jet quenching. Four different σ_{jet} values are shown, and for each plot there are results from Pythia simulations with two different generation cutoffs on the $2 \to 2$ scattering, $p_t^{\min} = 30$ GeV and $p_t^{\min} = 70$ GeV, so as to illustrate its impact. The results labelled "pp" reference always correspond to $p_t^{\min} = 30$ GeV with no smearing. Jet clustering has been performed with the anti-k_t algorithm [25] with $R = 0.4$, as implemented in FastJet [26, 27]

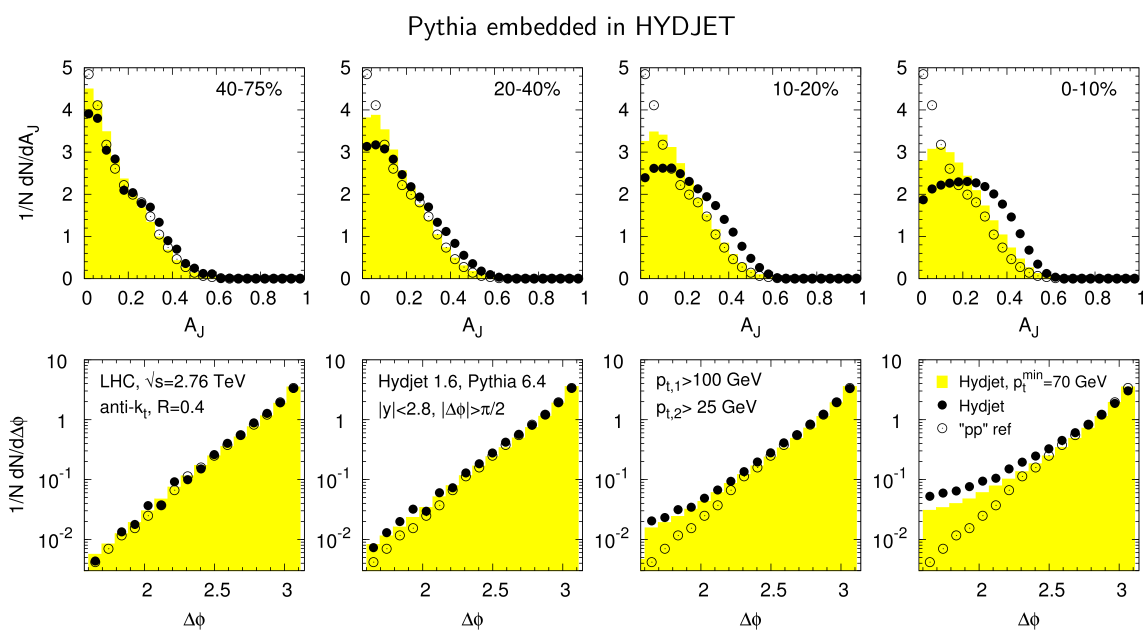

Fig. 3 Simulated distribution of A_J and $\Delta\phi$, as obtained when embedding Pythia events in a PbPb background described by HYDJET 1.6. None of the results in this figure involved jet quenching and the results obtained with HYDJET include a simple calorimeter simulation. Four different centrality regions are shown as indicated in the plots on the top row. For each plot there are results from Pythia simulations with two different generation cutoffs on the $2 \to 2$ scattering, $p_t^{\min} = 10$ GeV and $p_t^{\min} = 70$ GeV, so as to illustrate its impact. The results labelled "pp" reference always correspond to those of Fig. 2. Jet clustering has been performed with the anti-k_t algorithm [25] with $R = 0.4$, as implemented in FastJet [26, 27] and the heavy-ion background subtraction has been performed as described in [18] with the background density estimated using a StripRange of half-width 0.8 centred on the jet being subtracted

for the Gaussian smearing with increasing $\sigma_{\rm jet}$. If anything, the distortion of the A_J distribution for 0–10% central HYDJET collisions is slightly more pronounced at large A_J than with the highest Gaussian smearing we used, despite the smaller $\sigma_{\rm jet}$ value from HYDJET. This could perhaps be a consequence of non-Gaussianities in its fluctuations. The HYDJET results also confirm the importance of the choice of $p_t^{\rm min}$ cut on the $2 \to 2$ scatters.

While the above results suggest that fluctuations could be of relevance in interpreting the A_J distributions, one should not forget that the experiments have studied observables intended to signal the possible presence of important effects from fluctuations. One such observable is the fraction of energy inside a core of $R = 0.2$ within the jet. A fluctuation that enhances the leading jet's p_t would not necessarily be close to the centre of the jet and so should on average reduce the core energy fraction.[9] Preliminary data from ATLAS (p. 34 of [19]) show a stronger reduction in core energy fraction with increasing centrality than in the ATLAS HIJING simulations. In our HYDJET simulations, the core energy fraction decreases yet more rapidly, which at first sight suggests that its fluctuations could be excessive. On the other hand, we find that the agreement in absolute value is better for central collisions than for peripheral collisions, complicating the interpretation.[10] Another cross-check on fluctuations comes from the A_J distribution for jets with $R = 0.6$ (e.g. p. 48 of [19]). Since fluctuations should increase for a larger R, one would expect them to lead to an enhancement of the high A_J part of the $R = 0.6$ distribution. Vacuum QCD (and jet quenching) are expected to act in the opposite direction. The (unquenched) HYDJET simulation shows a fairly complicated behaviour however: the large A_J ($\gtrsim 0.4$) part of the distribution barely changes in going from $R = 0.4$ to $R = 0.6$, while the distribution increases for $A_J = 0.2$ (and decreases for A_J near zero). In contrast, the preliminary data decrease at large A_J and, within the (large) errors, barely change for moderate and small A_J, suggesting, possibly, some non-trivial interplay between an effect such as quenching and fluctuations.[11]

If fluctuations are relevant, as they seem to be,[12] then it is probably advantageous to attempt to unfold their effect, and/or to reduce their impact by raising the jet p_t thresholds. Additionally it may be of interest to investigate methods to suppress fluctuations (the method of [17] as used by CMS [14], or filtering/trimming/pruning [34–36]). Nevertheless one should be aware that such methods introduce potential biases of their own, as has been found in earlier studies [7–10, 18], and it then becomes important to quantify the interplay between any quenching and the noise reduction method.[13]

To conclude, we have found that fluctuations can significantly affect the dijet asymmetry A_J measured in [12]. A precise estimate of the contribution of fluctuations is therefore important to be able to quantify the degree of quenching that is present in the data. A first direct estimate of these fluctuations has appeared in preliminary form [21] since the original version of our article. It shows fluctuations that are well reproduced by our HYDJET simulations and consistent also, therefore, with the upper end of the range that we explored in the toy model. Quantitative use of the A_J data to constrain quenching therefore probably requires that the potential bias due to fluctuations (or from any techniques used to suppress them) be accounted for.

Acknowledgements We wish to thank Tancredi Carli, Brian Cole, Peter Jacobs, Christian Klein-Bösing, Michelangelo Mangano, Mateusz Ploskon, Sevil Salur, Peter Steinberg and Urs Wiedemann, for helpful conversations, comments and additional information. This work was supported in part by grants ANR-09-BLAN-0060 and PITN-GA-2010-264564.

Appendix

Since the appearance of the first version of this article, a number of questions have been raised concerning our analysis. Moreover new experimental results have become available. We address these questions here, also in light of the new data.

[9]This though is not entirely trivial, because the fluctuation may itself displace the centre of the jet. Furthermore any quenching of the leading jet may also reduce the core energy fraction.

[10]For the subleading jet, the centrality dependence is very similar for data and HYDJET, but the data are systematically about 0.15 below HYDJET.

[11]Data from CMS [14] on momentum flow in tracks, which appeared subsequent to the first version of this article, also indicate some genuine component of quenching.

[12]We recognise that this interpretation may not be uniformly subscribed to by the LHC experiments and look forward to discussion of the most recent (and forthcoming) data in the hope of reaching a consensus on this point.

[13]Such methods discard low-momentum components of the jets, exploiting the fact that the background is almost entirely made of low-momentum particles, while for a pp jet only a small fraction of its total momentum is contained in low-momentum components. In the presence of quenching, however, a larger, but unknown, fraction of the jet's energy may be concentrated in low-momentum components. Discarding these components is then not without risks. Special care should also be taken with infrared or collinear unsafe seeded jet algorithms, as quenching may cause a jet's high central energy density (the seed) to be redistributed over a broader region of the calorimeter. Further concerns, specific to the method used by CMS, are discussed in Appendix A.4.

A.1 Details of our Gaussian smearing procedure

In the discussions that followed the appearance of our article, one question that arose concerned the details of our Gaussian smearing procedure, which we had originally omitted for brevity. The procedure is the following: we generate Pythia events (pp, $\sqrt{s} = 2.76$ TeV, DW tune); to these we add a low density of "ghost" particles (10 per unit area), which have infinitesimal momentum and serve to ensure that there are no substantial empty regions in the event; we then run the anti-k_t algorithm with $R = 0.4$ on the combination of Pythia and ghost particles. For each jet that is found (however small its momentum, and independently of whether it involves Pythia particles or just ghost-particles) we add to it a random p_t, chosen according to a Gaussian distribution of zero mean and dispersion σ_{jet}. We then consider only the two hardest jets, requiring that they both be above the 25 GeV threshold.

A criticism was made [37] that only "hard" jets should be fluctuated and that if this choice was made then the deformation of the A_J distribution would differ substantially from that seen in Fig. 2. The criticism may have its origins in the fact that one of the LHC experiments, CMS, uses a seeded jet algorithm. Depending on the seed threshold, then it might indeed be the case that a hard core is a prerequisite for a jet to be found.[14] For a non-seeded algorithm such as anti-k_t, fluctuations anywhere in the event may cause a jet to be found, even if there was no corresponding genuine underlying hard jet. This has to be accounted for in the choice of original jets that receive fluctuations. We note that had we not fluctuated zero- and low-p_t jets we would not have reproduced the broadening of the low $\Delta\phi$ tail in Fig. 2 (which for $\sigma_{\text{jet}} = 20$ GeV is comparable to ATLAS's results for 0–10% centrality).

One criticism that would be legitimate is that some fraction of the anti-k_t jets have a very small area and should therefore be subject to smaller fluctuations, whereas we assigned identical fluctuations to all jets. We have examined the impact of a modified version of our procedure, in which the fluctuations scale in proportion to the square-root of the jet area. The results show slightly larger fluctuation-induced asymmetries, perhaps because a modest fraction of anti-k_t jets have areas larger than πR^2.

[14] CMS actually has a quite low seed threshold, of 1 GeV [14], and so in practice the heavy-ion background may produce a high multiplicity of seeds in its own right. The choice of seed threshold is delicate precisely because too low a value brings in many "fake" seeds and too high a value may cause genuine jets to be missed, especially if quenching changes the relative proportion of high-p_t particles in the jet. Additionally, seeds are intrisincally collinear unsafe.

A.2 Fluctuations in ALICE data and HYDJET simulations

To date, the most direct experimental constraint on σ_{jet} comes from an ALICE result presented in a talk [21] a few weeks after the appearance of our note. This involves a measurement of the resolution in the reconstruction of jets from charged tracks only, tested via the embedding of single-track jets. The background subtraction method used there is the area/median method of FastJet. We can directly compare to it by applying our analysis procedure on the charged tracks from HYDJET, with a single additional embedded hard track.

That comparison is given in Fig. 4, which shows the difference between the reconstructed p_t of the jet that contains the track and the p_t of the track itself. The agreement between the ALICE and HYDJET results is striking, especially considering that our HYDJET simulation had not been directly tuned to LHC data. Quantitatively this can seen by comparing the $\sigma_{\text{jet(chg)}}$ values as obtained from the ALICE data with those from the simulation. We find $\sigma_{\text{jet(chg)}} \simeq 11.5$ GeV from the ALICE data and 11.4 GeV in the HYDJET simulation.[15]

Several factors intervene in comparing these results to the σ_{jet} value of 17 GeV discussed in the main text for full jets embedded in HYDJET. Firstly, in going from the embedding of a single track to that of a full jet, an extra increase of a few percent may arise (e.g. due to back-reaction [18]). More importantly, assuming that a fraction $f_{\text{chg}} \simeq 0.6$ of the energy flow is carried by charged particles, one may expect an additional factor that is somewhere between $\sim 1/\sqrt{f_{\text{chg}}} \simeq 1.3$ (taking charged and neutral components to be uncorrelated) and $\sim 1/f_{\text{chg}} \simeq 1.7$ (for 100% correlated charged and neutral components). Finally there will be additional fluctuations from the calorimetric nature of jet measurements. Combining all these factors gives a result that is consistent with the $\sigma_{\text{jet}} \simeq 17$ GeV quoted in the main text.

Ultimately therefore, the ALICE results support the choices that we made in estimating the possible order of magnitude of fluctuation-induced contributions to the jet-asymmetry measurement. Note however that other issues also need to be taken in to account at the 1–2 GeV level

[15] There is a small residual shift between the ALICE and HYDJET results. When it is taken into account, the visual agreement in Fig. 4 becomes perfect. The precise origin of this small difference has not been identified, but small differences in the subtraction procedure can lead to such shifts without affecting the $\sigma_{\text{jet(chg)}}$ value [18]. Note that the $\sigma_{\text{jet(chg)}}$ can, however, be affected by the choice of ghost area. A smaller area can reduce it by 0.5 GeV. We have verified that Fig. 3 remains essentially unchanged when using a smaller ghost area. Note that the $\sigma_{\text{jet(chg)}}$ values quoted by ALICE were obtained from Gaussian fits to the $\Delta p_t < 0$ region. Such fits give $\sigma_{\text{jet(chg)}}$ values that are about 2 GeV smaller than results derived from the full distribution, which are more relevant to our studies here.

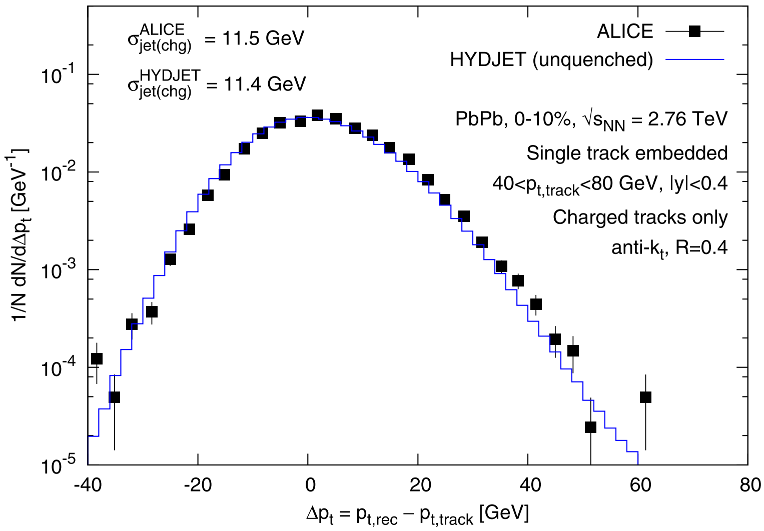

Fig. 4 Comparison of our HYDJET simulation to ALICE data [21], showing the distribution of $\Delta p_t = p_{t,\mathrm{rec}} - p_{t,\mathrm{track}}$ i.e. the difference in transverse momentum between a reconstructed charged-track jet (anti-k_t, $R = 0.4$) and the single embedded charged track contained within it. Δp_t is calculated after background subtraction with the FastJet median/area method. The jets have been reconstructed using charged particles with $|\eta| < 0.8$ and $p_t > 150$ MeV, whose masses have been set to zero by rescaling their energy. The background estimation in the HYDJET case used the k_t algorithm [38, 39] with $R = 0.4$, with particles and ghosts (of area 0.01) up to $|y| = 0.8$ and a global range up to $|y| = 0.4$ (excluding the two hardest jets within $|y| < 0.8$). We understand that these choices coincide with those made by ALICE

(for example detector effects). An analysis at this level of accuracy can therefore probably only be performed in conjunction with a fu ll detector simulation.

A.3 Suitability of calorimeter simulation

One objection that has been raised concerning our HYDJET results is that our toy calorimeter simulation suffered from an overly pessimistic resolution. To obtain a detailed description of jet response, ideally many effects need to be taken into account, including tower thresholds, different kinds of noise term that are independence of energy, scale as $1/\sqrt{E}$ and as $1/E$, different responses to photons and charged hadrons, the effect of magnetic fields, and the degradations of resolution due to detector elements that lie between the interaction point and the calorimeter. A full simulation of all these effects goes beyond the scope of this article, therefore we made a simple approximation involving towers of size 0.1×0.1 with a resolution of $0.8/\sqrt{E}$, together with the removal of charged tracks with $p_t < 0.5$ GeV (on the grounds that they would be bent away from the calorimeter by the magnetic field). The $0.8/\sqrt{E}$ term is larger than the corresponding term for the ATLAS hadronic calorimeter ($\sim 0.5/\sqrt{E}$), however this difference is justified by the fact that we neglect many other sources of detector fluctuation. The validation of this statement is given through Fig. 5, which compares the jet resolution that we have observed with our calorimeter (matching calorimeter jets within $\Delta R < 0.25$ of the two hardest particle-level jets in an event) to that found by ATLAS. One sees that rather than overestimating calorimeter fluctuations, we actually underestimate them by 5–10% over the full range of p_t in which jet resolution measurements exist. Note also that ATLAS has shown that its calorimeter response is similar for jets and heavy-ion backgrounds (p. 37 of [19]).

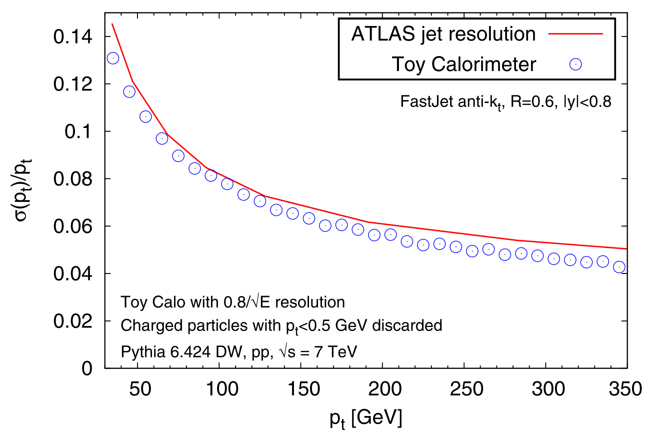

Fig. 5 Comparison of jet resolution obtained with our toy calorimeter to the measured ATLAS jet resolution [40]

A further potential issue comes from the fact that an experiment's magnetic field, by bending particles differently according their p_t, may smear any angular correlations that are present in the background fluctuations. Our calorimeter simulation did not by default consider the impact of a magnetic field (other than by removing charged particles with

$p_t < 0.5$ GeV). We have, however, verified that if one accounts for the effect of a magnetic field on the charged-particles' azimuth when they reach the calorimeter, the FastJet median/area estimate of fluctuations is reduced by an amount of order 1%. This value was obtained with a configuration similar to that used by ATLAS, i.e. a longitudinal magnetic field of strength $B = 2$ T, with a calorimeter at a radius of 1.5 m from the beam. This result gives us confidence that our original approximation was not unreasonable.

If is to be noted that magnetic fields could also have an impact on measurements of quenched jets (independently of background-related issues), insofar as quenching may alter the relative fractions of different momentum components within a jet and therefore also give an appearance of additional jet broadening.

A.4 The CMS jet-reconstruction procedure

It was not the purpose of this article to discuss the CMS results [14], insofar as they appeared subsequent to the first version of this article. However, certain criticisms of our work have been made based on results presented by CMS, and so deserve comment.

An objection that has been raised is that CMS explicitly show jet resolution results that are incompatible with the values we have investigated. For example, Fig. 4f of [14] indicates that 40 GeV jets (0–10% centrality) have about 20% resolution, i.e. a $\sigma_{\text{jet}} \simeq 8$ GeV, well below the largest values that we have discussed here. In this context, however, it is important to be aware that CMS's jet reconstruction procedure differs substantially from ATLAS's. One of the differences is that the method used to subtract the heavy-ion background involves a noise reduction technique [17] that estimates the mean μ and standard deviation σ_{tower} of the calorimeter towers' p_t deposits (after excluding hard jets) and then subtracts $\mu + \sigma_{\text{tower}}$ from each tower's p_t. Only towers that are positive are then retained.

To understand the potential benefits and biases of this method, let us make the assumption that μ and σ_{tower} are well determined (there are a number of complications in their practical determination, e.g. with respect to the exclusion of hard jets, which may degrade the performance of the method with respect to the analysis that follows). Let us also assume purely Gaussian noise (again, this is probably optimistic). Then the fraction of towers retained is

$$\int_{\sigma_{\text{tower}}}^{\infty} dx \, \frac{1}{\sqrt{2\pi}\,\sigma_{\text{tower}}} e^{-\frac{x^2}{2\sigma_{\text{tower}}^2}} \simeq 0.1587, \tag{A.1}$$

where $x = p_{t,\text{tower}} - \mu$. Since all of these towers are positive, they induce a systematic offset in the overall reconstructed jet momentum

$$\begin{aligned}\langle \delta p_{t,\text{jet}}^{\text{noise}} \rangle &= N_{\text{tower}} \langle \delta p_{t,\text{tower}}^{\text{noise}} \rangle \\ &= N_{\text{tower}} \int_{\sigma_{\text{tower}}}^{\infty} dx \, \frac{(x - \sigma_{\text{tower}})}{\sqrt{2\pi}\,\sigma_{\text{tower}}} e^{-\frac{x^2}{2\sigma_{\text{tower}}^2}} \\ &\simeq 0.0833\, \sigma_{\text{tower}}\, N_{\text{tower}},\end{aligned} \tag{A.2}$$

where N_{tower} is the total number of towers that are contained in a jet (πR^2 divided by the tower area, which is 0.087×0.087, i.e. $N_{\text{tower}} \simeq 104$ with $R = 0.5$ as used by CMS). For $\sigma_{\text{tower}} \simeq 1$–2 GeV, this would correspond to an 8–16 GeV bias.

The residual fluctuations after the noise suppression can be estimated as

$$\left(\sigma_{\text{jet}}^{\text{noise-suppressed}}\right)^2$$

$$= N_{\text{tower}} \left[\left\langle \left(\delta p_{t,\text{tower}}^{\text{noise}}\right)^2 \right\rangle - \left\langle \delta p_{t,\text{tower}}^{\text{noise}} \right\rangle^2 \right] \tag{A.3a}$$

$$= N_{\text{tower}} \left[\int_{\sigma_{\text{tower}}}^{\infty} dx \, \frac{(x - \sigma_{\text{tower}})^2}{\sqrt{2\pi}\,\sigma_{\text{tower}}} e^{-\frac{x^2}{2\sigma_{\text{tower}}^2}} - \left\langle \delta p_{t,\text{tower}}^{\text{noise}} \right\rangle^2 \right] \tag{A.3b}$$

$$\simeq (0.262\, \sigma_{\text{tower}})^2\, N_{\text{tower}}, \tag{A.3c}$$

i.e. a 74% reduction in the noise as compared to subtraction procedures without noise suppression, which just give $\sigma_{\text{jet}}^2 \simeq \sigma_{\text{tower}}^2 N_{\text{tower}}$. This is a potential strength of the CMS noise-reduction technique, but it comes at the price of introducing a significant p_t offset, (A.2). Since noise-reduction has such a large impact on the fluctuations it is not possible to draw any conclusion about ATLAS results based on the quoted CMS jet resolution after noise-suppression.

In practice, in simulations that embed hard pp jets in a heavy-background, the offset of (A.2) will not be directly seen. This is because embedded hard jets are not just pure noise, but involve some number of towers that are far above the $\mu + \sigma_{\text{tower}}$ threshold. These towers will all be retained. However, relative to the original pp towers, there will now be an offset of $-\sigma_{\text{tower}}$ for each of these towers. Defining the calorimeter "occupancy" of a normal pp jet to be f (i.e. a pp jet contains on average $f N_{\text{tower}}$ active towers), then the total offset from this effect will be

$$\left\langle \delta p_{t,\text{jet}}^{\text{hard}} \right\rangle \simeq -f N_{\text{tower}} \sigma_{\text{tower}}. \tag{A.4}$$

In the limit in which f is small its impact can be neglected in (A.2), (A.3). For hard QCD vacuum jets we find that it has a value $f \simeq 0.1$.[16]

[16] It is not clear however whether this is truly small enough for its quantitative impact in (A.2), (A.3) to be entirely negligible.

Taking into account this effect and the offset of (A.2), gives us an overall offset of

$$\langle \delta p_{t,\mathrm{jet}}^{\mathrm{overall}} \rangle = \langle \delta p_{t,\mathrm{jet}}^{\mathrm{noise}} \rangle + \langle \delta p_{t,\mathrm{jet}}^{\mathrm{hard}} \rangle \simeq (0.0833 - f) N_{\mathrm{tower}} \sigma_{\mathrm{tower}}. \tag{A.5}$$

Thus the net bias is small, but only due to a fortuitous cancellation between two effects with very different physical origins.[17] Both of these effects are at the same 10% level as the overall impact of quenching (e.g. Fig. 12 of [14]). Furthermore, it is not immediately clear that f for quenched jets is the same as for pp jets and one may even expect it to be larger, especially for the away-side jet, leading to an additional negative offset for that jet, thereby artificially enhancing the asymmetry. Therefore any quantitative analysis of quenching in heavy-ion collisions that relies on noise reduction should also perform an analysis of systematic errors due to any biases associated with potential medium-induced modifications of f.

The discussion also implies that it is difficult to relate the large number of supporting plots by CMS (e.g. track-properties of calorimeter jets) directly to the ATLAS case.

References

1. U.A. Wiedemann, arXiv:0908.2306 [hep-ph]
2. D. d'Enterria, arXiv:0902.2011 [nucl-ex]
3. J. Casalderrey-Solana, C.A. Salgado, Acta Phys. Pol. B **38**, 3731–3794 (2007). arXiv:0712.3443 [hep-ph]
4. A. Majumder, M. Van Leeuwen, arXiv:1002.2206 [hep-ph]
5. P. Jacobs, X.-N. Wang, Prog. Part. Nucl. Phys. **54**, 443–534 (2005). hep-ph/0405125
6. M. Gyulassy, I. Vitev, X.-N. Wang et al., in *Quark Gluon Plasma*, ed. by R.C. Hwa et al. (2003), pp. 123–191. nucl-th/0302077
7. S. Salur (STAR Collaboration), Eur. Phys. J. C **61**, 761 (2009). arXiv:0809.1609 [nucl-ex]
8. S. Salur (STAR Collaboration), Nucl. Phys. A **830**, 139C (2009). arXiv:0907.4536 [nucl-ex]
9. M. Ploskon (STAR Collaboration), Nucl. Phys. A **830**, 255C (2009). arXiv:0908.1799 [nucl-ex]
10. E. Bruna (STAR Collaboration), arXiv:1010.3184 [nucl-ex]
11. Y.S. Lai for the PHENIX collaboration, arXiv:0911.3399 [nucl-ex]
12. The ATLAS Collaboration, arXiv:1011.6182 [hep-ex]
13. B. Wyslouch for the CMS collaboration, Presentation at CERN, 2 December 2010, http://indico.cern.ch/getFile.py/access?contribId=1&resId=1&materialId=slides&confId=114939
14. The CMS Collaboration, arXiv:1102.1957 [nucl-ex]
15. J. Casalderrey-Solana, J.G. Milhano, U.A. Wiedemann, arXiv:1012.0745 [hep-ph]
16. J. Alwall et al., Eur. Phys. J. C **53**, 473 (2008). arXiv:0706.2569 [hep-ph]
17. O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C **50**, 117–123 (2007)
18. M. Cacciari, J. Rojo, G.P. Salam, G. Soyez, Eur. Phys. J. C **71**, 1539 (2011). arXiv:1010.1759 [hep-ph]
19. B. Cole for the ATLAS collaboration, Presentation at CERN, 2 December 2010, http://indico.cern.ch/getFile.py/access?contribId=0&resId=5&materialId=slides&confId=114939
20. M. Cacciari, G.P. Salam, G. Soyez, J. High Energy Phys. **0804**, 005 (2008). arXiv:0802.1188
21. C. Klein-Bösing, Talk presented on behalf of the ALICE collaboration at "HI at the LHC: a first assessment", p. 23. CERN March 4th 2011, http://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=118273
22. T. Sjostrand, S. Mrenna, P. Skands, J. High Energy Phys. **05**, 026 (2006). hep-ph/0603175
23. M.G. Albrow et al. (TeV4LHC QCD Working Group), arXiv:hep-ph/0610012
24. P. Jacobs, arXiv:1012.2406 [nucl-ex]
25. M. Cacciari, G.P. Salam, G. Soyez, J. High Energy Phys. **0804**, 063 (2008). arXiv:0802.1189 [hep-ph]
26. M. Cacciari, G.P. Salam, Phys. Lett. B **641**, 57 (2006). hep-ph/0512210
27. M. Cacciari, G.P. Salam, G. Soyez, http://www.fastjet.fr
28. X.-N. Wang, M. Gyulassy, Phys. Rev. D **44**, 3501–3516 (1991)
29. I.P. Lokhtin, A.M. Snigirev, hep-ph/0312204
30. I.P. Lokhtin, A.M. Snigirev, Eur. Phys. J. C **45**, 211 (2006). arXiv:hep-ph/0506189
31. K. Aamodt et al. (The ALICE Collaboration), arXiv:1012.1657 [nucl-ex]
32. K. Aamodt et al. (The ALICE Collaboration), arXiv:1011.3916 [nucl-ex]
33. M. Cacciari, G.P. Salam, Phys. Lett. B **659**, 119 (2008). arXiv:0707.1378
34. J.M. Butterworth, A.R. Davison, M. Rubin, G.P. Salam, Phys. Rev. Lett. **100**, 242001 (2008). arXiv:0802.2470
35. D. Krohn, J. Thaler, L.T. Wang, J. High Energy Phys. **1002**, 084 (2010). arXiv:0912.1342
36. S.D. Ellis, C.K. Vermilion, J.R. Walsh, Phys. Rev. D **81**, 094023 (2010). arXiv:0912.0033
37. C. Roland, Talk presented on behalf of the CMS collaboration at "HI at the LHC: a first assessment", CERN March 4th 2011, http://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=118273
38. S. Catani, Y.L. Dokshitzer, M.H. Seymour, B.R. Webber, Nucl. Phys. B **406**, 187 (1993)
39. S.D. Ellis, D.E. Soper, Phys. Rev. D **48**, 3160 (1993). hep-ph/9305266
40. The jet resolution has been extracted from the "Global Sequential" (GS) curve of the first plot from http://twiki.cern.ch/twiki/pub/AtlasPublic/JetResolutionPreliminaryResults, as extracted on 13 April 2011

[17] The cancellation may be less fortuitous that it seems, since the choice to subtract $\mu + x\sigma_{\mathrm{tower}}$ with $x = 1$ is a priori arbitrary and may have been tuned specifically to some subset of vacuum QCD jets. Note also that fluctuations in f from one jet to another can be substantial and this can partially counteract the reduction in σ_{jet} due to the noise suppression of the background fluctuations.